High Performance Vertical Organic Transistor Using Sheet Metal Base

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Abstract
High performance vertical-type organic transistors were fabricated using a simple structure composed of organic/ metal/organic layers. This device could modulate a sheet current between emitter and collector by a voltage application to the thin metal base electrode inserted in between. When C_{60} and perylene derivatives were used for the channel layer, the modulated collector current exceeded 300 mA/cm^2 by applying only several volts of base voltage, and cut-off frequency exhibited 2.6kHz. The operating mechanism for this device was discussed from the viewpoint of metal base transistors.

Introduction
Recently, organic transistors have attracted considerable attention due to their flexibility and low cost fabrication.[1, 2] So far, organic transistors mostly mean field effect transistors (FET) shown in Fig. 1(a), but FETs using organic materials show low response speed and small current modulation mainly because of their low charge mobility. To solve this problem, it is important and necessary not only to improve the electrical parameters of the organic material itself, but also to investigate the device structure and mechanism suitable for organic devices. From the latter viewpoint, the vertical structure, in which the current carriers flow across the organic film, was proposed to shorten channel length. In these devices, polymer grid triode[3,4] (PGT) and organic static induction transistors[5,6] (organic SIT) were reported, and we also proposed charge injection controlled organic transistor[7] (CICT) based on a novel principle.

These devices have a sandwich structure of an organic film with a third electrode embedded in the organic film in a form of mesh, and consequently, have the advantage that a sheet current (though mesh) can be modulated. (Fig. 1(b)) The mesh third electrode of PGT was composed of self-assembly polyaniline-network, and that of SIT and CICT was striped metal electrode fabricated by using shadow mask. However, the mesh third electrode technique has also a disadvantage, that is, the current modulating area is limited to the region near the edge of the mesh electrode. Consequently, very fine patterns comparable to the film thickness are required for large current modulation.

In this letter, we report a very high performance vertical transistor having a uniform metal base called metal base organic transistor (MBOT). This device has a more simple layered structure composed of organic/metal/organic layer, requiring no striped patterning. (Fig. 1(c)) In spite of the simplification, this device showed much higher performance of large current modulation and low driving voltage. The curious mechanism on the current amplification will be also discussed.

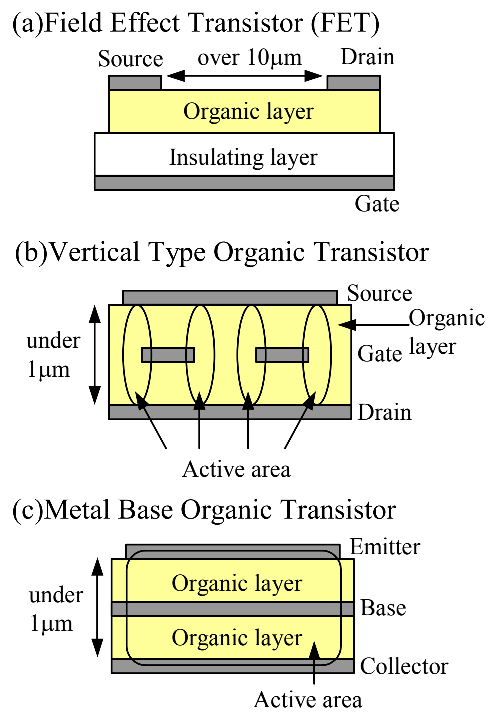

Figure 1. Construction of various organic transistors

Experimental
The device (Fig. 2) was fabricated by vacuum evaporation under 1×10^{-3} Pa. The n-type organic semiconductor N,N'-dimethyl-3,4,9,10-perylene-tetracarboxylicdiimide was de-posited with a thickness of 500 nm on a clean ITO glass substrate. The inserted aluminum electrode, typically 20 nm thick, was deposited on the top of this layer. Another upper organic layer of n-type semiconductor C_{60} (100 nm), and the top Ag electrode (30 nm) were provided. The active area where three electrodes are overlapped was 0.02 cm^2. The measurements were carried out using two source-measure units (Keithley Instruments Inc., model 236) under vacuum condition (10^{-1} Pa) at room temperature.

Hereafter, we called the top Ag the emitter and the embedded Al the base, and the bottom ITO the collector, referring to three terminal bipolar transistors. The collector voltage (V_c) of an output voltage was applied between the collector and emitter electrodes using a negative bias on the emitter. The base voltage (V_b) of an input voltage was applied between the emitter and base electrodes using a negative bias on the emitter.

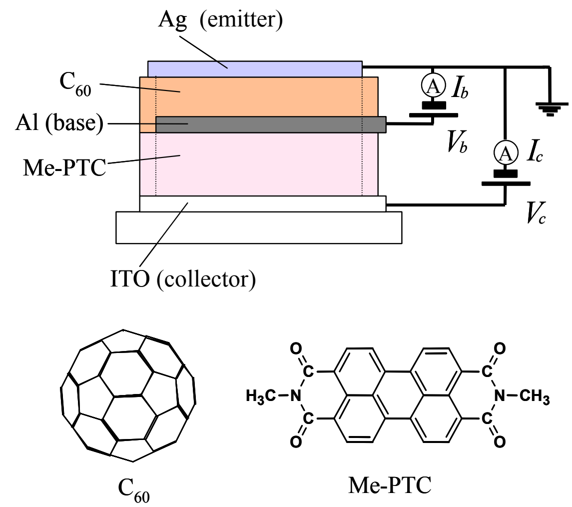

Figure 2. Device structure of vertical-type organic transistors and measurement circuits used for evaluating transistor performance.

Results and Discussion

Transistor Characteristics

Figure 3 shows current-voltage curves between the emitter and collector plotted for different constant base voltages (V_b). At V_b = 0 (shorted), a small collector current was observed on applying V_c. However, the application of V_b markedly increased collector current (I_c), and finally, I_c exceeded 300 mA/cm^2 (at V_c = 5 V) for only 3 V application to base electrode. This means that a very high current density, enough to drive OLED devices, can be modulated by a small external voltage. The ON/OFF ratio reached around 100 (at I_c = 280 mA/cm^2), being rather high for vertical-type transistors.

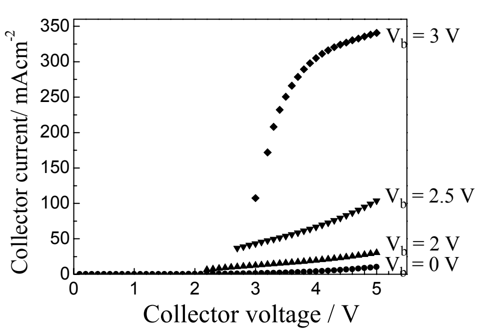

Figure 3. Collector current (I_c) vs. collector voltage (V_c) characteristics of vertical transistors

We evaluated the current amplification factor (h_{FE}) defined for bipolar transistors, because the inserted electrode of this device was not isolated electrically from the channel between emitter and collector. The value of h_{FE}, which is defined as the ratio of I_c (output current) to I_b (input current), reached as high as 180 (Fig. 4). This indicates that the change in the output current was much larger than that of the input current when the base voltage was applied. Thus, this simple device was found to act as a bipolar-like transistor capable of current amplification.

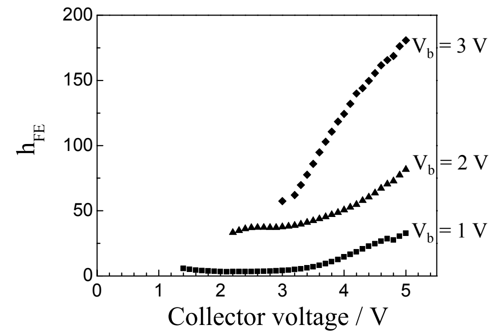

Figure 4. Current amplification factor (h_{FE}) vs. collector voltage (V_c) characteristics of vertical transistors

Next, we measured the response speed and frequency characteristics of this device, which are another important performance of transistors. Figure 5 shows the typical collector current waveform for alternating base voltage at 400 Hz. The collector current was followed well the input wave shape without phase delay.

To investigate the response speed quantitatively, we defined the gain as the follow equation, which is index of collector current decreasing with an increasing in frequency:

$$\mathrm{Gain} = 20\log(I_c(f)/I_c(0))$$

where $I_c(f)$ is modulation of collector current with base voltage at frequency of f, and $I_c(0)$ is the value for DC input. Figure 6 shows the gain for various frequencies of V_b. The gain decreased with the increase of frequency beyond 1 KHz. The cutoff frequency of –3 dB attenuation was estimated to be 2.6 kHz. In most organic FETs, the cutoff frequency remains several hundreds Hz because of its long channel length and low mobility of organic materials. Therefore, it is concluded that the MBOT has considerable high frequency response. This characteristic also reflects an advantage of a vertical structure device having shorter channel length than coplanar FET.

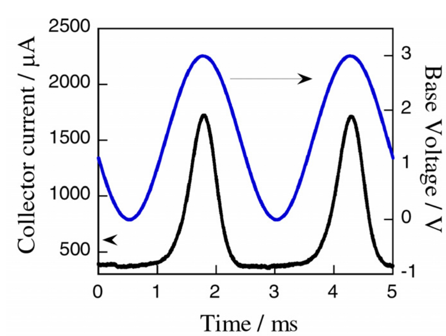

Figure 5. Transient responses of the collector currents for the alternating base voltage. The V_b was applied 3 V under a constant V_c of 5 V.

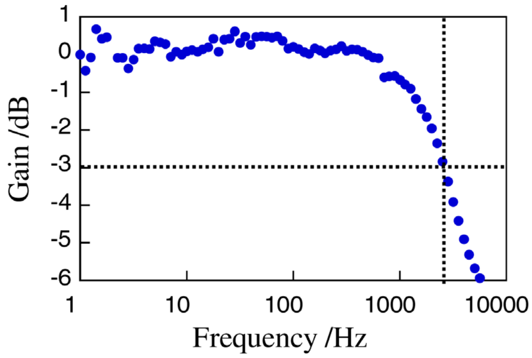

Figure 6. Frequency characteristics of MBOT. The V_b was applied 3 V under a constant V_c of 5 V.

Dependence of Base Film Thickness and Organic Material

Such transistor characteristics are not necessarily observed in all devices having an organic/metal/organic structure. The most important requirement is to use a thin base electrode, because the injected carriers from the emitter pass through the base electrode without flowing into the input circuit. Therefore, we evaluated the base transmission factor α, defined as the ratio of the emitter current (= $I_c + I_b$) to the collector current, and directly connected to h_{FE} by the following equation in a grounded-emitter circuit:

$$h_{FE} = \frac{\alpha}{1-\alpha}$$

Figure 7 shows the dependence of α on thickness of the base electrode. The value of α decreased with increasing the thickness of the base electrode. However, it should be noted that the value of α approached unity in less than 40 nm, which means that almost all the current from emitter flows through the base electrode, although the base electrode is not electrically isolated. In fact, the base current remained less than 1 mA/cm^2 during operation of this device, even when large current more than 100 mA/cm^2 flows between emitter and collector. This is the reason why the current amplification can be observed.

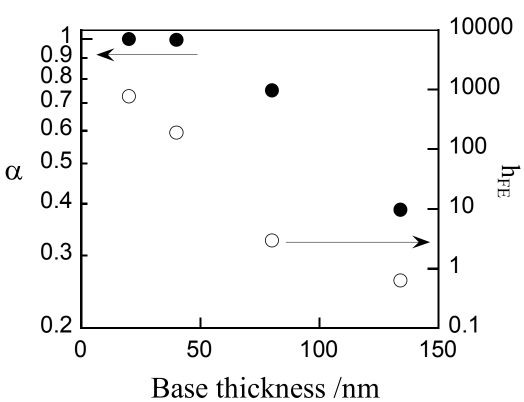

Figure 7. Effect of base film thickness on current amplification factor (hFE) and current transmission factor (a), defined as the ratio of collector current to emitter current (= Ic + Ib), at Vc = 5 V and Vb = 4 V.

Another key to obtain current amplification is the kind of organic materials used. Table 1 shows transistor charac-teristics using various combinations of n-type organic materials, i.e, C_{60}, Me-PTC, naphthalene tetracarboxylicdian-hydride (NTCDA).

Table 1: Transistor characteristics using various combinations of organic materials. Electrode was using ITO, 20nm Al and Ag as collector, base and emitter, respectively.

Collector	Emitter	On-Off ratio	ΔIc(mAcm^{-2})	h_{FE}
Me-PTC	C_{60}	100	300	200
Me-PTC	NTCDA	8	90	260
Me-PTC	Me-PTC	2	3.25	35
NTCDA	C_{60}	40	4.65	15
C_{60}	C_{60}	15	0.0075	< 1

As far as we have attempted, the best performance was achieved in the combination of C_{60} and Me-PTC as the emitter and collector layer, respectively, although some amplification was observe d in other combination of electron-transport materials, while hole-transport materials used for OLED devices did not show any amplification. This suggests that the modulated current is mainly due to electrons injected from emitter electrode.

Operating Mechanism

The mechanism of the current amplification is not clear except the fact that the metal film without any patterning works as a base electrode. First, we consider the issue whether the thin metal base electrode covers the organic film surface fully and smoothly, or covers partially like a mesh electrode. In the latter case, the mechanism might be similar to the organic SIT, which modulates the current flowing through openings of the mesh electrode. The early study on SIT reported that current modulation was observed in a device having a mesh-like gate electrode prepared by deposition of a very thin electrode film.[5] However, in our case, a large current modulation was obtained even for the thickness no less than 40 nm, which seemed to cover the surface almost fully from observation of a scanning electron microscope. Even if there were some openings, the area ratio of openings must be very small. Thus, it is difficult to explain the very large area-averaged current density over 100 mA/cm^2.

Thus, we suggest another mechanism to explain the high transmission factor of the emitter current passing through the metal base electrode. Actually, such a transistor has been known as metal base transistors (MBT) in inorganic systems. The MBT proposed in the 1960's has a similar structure of semiconductor/metal/semiconductor, where the emitter current modulated by the base voltage passes through the base electrode as hot electrons and plunges into the semiconductor layer of the collector side.[8] Since it includes a hot electron process, an increasing thickness of the base electrode exponentially decreases the value of α, which is associated with a mean free path length of electron in the metal. Because a mean free length in aluminum was reported to be 15 ~

50 nm, the base thickness of 20 nm of our device seems to be too thick to attain high α approaching unity. On the other hand, there has been a recent report on a high performance MBT composed of C_{60}/Au/Si structure, showing a high α over 0.99 for base electrode thickness of 60 nm.[9] Therefore, we presently consider that this mechanism is rather reasonable in our device, but further investigation on the base electrode and the channel of the emitter current is required.

Conclusion

We have successfully fabricated high performance organic transistors with a simple vertical structure composed of organic/metal/ organic layers. When a sufficiently thin base electrode (about 20 nm thickness) and appropriate semiconductor materials were employed, current modulation of over 100 mA/cm2 could be obtained for several volts of base voltage. Because this device has a planar active area without any striped pat tern, it can easily be combined with OLED devices for active matrix systems.

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Author Biography

Shin-ya Fujimoto received the B. Eng. in 2001 and the M. Eng. in 2003 from Osaka University in Applied Chemistry. He has investigated organic semi-conductors applications as a Dr. course student under the direction of Prof. Masaaki Yokoyama in Graduate School of Engineering.